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Long term multi-wavelength analysis of the flat spectrum radio quasar OP 313

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Summary. — The Flat Spectrum Radio Quasar (FSRQ) OP 313 showed intense γ-ray activity from November 2023 to March 2024, as observed by the *Fermi* Large Area Telescope (*Fermi*-LAT). We present a multi-wavelength analysis covering 15 years of *Fermi*-LAT observations, from August 2008 to March 2024. From the γ-ray light-curve study, we identified different periods of high-state activity, called flaring states. These are compared with the data available from other facilities. The long-term multi-wavelength activity of the source was investigated using a wide dataset extending from radio to the γ-ray bands. We investigated the kinematics of the radio jet to probe the mechanisms producing the galaxy's flaring activity. This approach helps us to understand the mechanisms involved in particle acceleration inside the jet, and how radiation in different wavelengths is connected.

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1. – Introduction

Blazars are the class of jet-dominated, radio-loud Active Galactic Nuclei (AGN) whose relativistic jets point close to our line of sight [1]. These objects are characterized by variations in the flux, visible in different energy bands. Blazars are classified into two distinct categories: FSRQs and BL Lacs. FSRQs have strong and broad optical emission lines and high bolometric luminosities [2]. On the other hand, in BL Lacs the optical lines are weak, and they have lower bolometric luminosities.

Blazars are extremely important because the γ-ray sky above 10 GeV is dominated by their emission, and they have been surveyed by the *Fermi* Large Area Telescope (LAT) on board the *Fermi* Gamma-ray Space Telescope since the summer of 2008 [3].

OP 313 ($z = 0.997$) [4] exhibited a flux increase at the end of November 2023, with the peak of the emission on November 24th 2023, at energies larger than 100 MeV, 40 times higher than the value reported in the 4FGL [5] catalog (2.4×10^{-9} photons/cm^2/s from 0.1 to 100 GeV). This flare led the *Fermi* Collaboration to publish an Astronomer's Telegram (ATel) on this flare [6]. OP 313 was remarkably detected also by the Large Sized Telescope-1 (LST-1) of the Cherenkov Telescope Array Observatory (CTAO) located at La Palma [7]. Another major γ-ray flare from this source was seen on February 27th, 2024. The detected flux was the highest ever detected by *Fermi* Large Area Telescope (*Fermi*-LAT), 60 times larger than the value reported in the 4FGL catalog [8].

2. – Multi-wavelength data analysis

We performed *Fermi*-LAT data analysis using the *ScienceTools*(1) v2.2 and the `fermipy` v1.1 Python package. We computed the adaptive binned light-curve using the algorithm developed by [9] and detected the statistically significant variations in it using the Bayesian Blocks algorithm [10] implemented inside `astropy`(2). We used the same approach reported in [11] to distinguish flaring from quiescent states of the source. We considered the average flux, weighted by the time duration of each bin, in the low-activity period from December 2014 to August 2018 as a proxy of the quiescent state. All the Bayesian blocks with a flux level higher than this value (4.93×10^{-8} photons/cm^2/s) represent the flaring states of the source, all the blocks with a flux level lower than this represent the quiescent states.

We analyzed the OP 313 publicly available data(3) [12] of *Swift*-X-Ray Telescope (XRT) in a time window from August 2008 to March 2024. We performed the analysis adopting the spectral fitting package XSPEC v12.13.1 [13] and the python package PyXspec v2.1.4 available in the HEASOFT(4) software v.6.33.1, together with the calibrated source background (CALDB, v20220331), and response files. In our analysis, we applied the `cstat` statistic, a column density value of $n_H = 0.0123 \times 10^{22}$ particles/cm^2 and the redshift fixed to $z = 0.9973$. We fitted the spectrum using a power-law with an exponential cut-off to take into account the photoelectric absorption.

We processed the *Swift*-UVOT datasets and analyzed them using the `uvotimsum` and `uvotsource` tasks in HEASOFT. The available UVOT observations were performed using

(1) `https://fermi.gsfc.nasa.gov/ssc/data/analysis/software/`.
(2) `https://docs.astropy.org/en/stable/api/astropy.stats.bayesian_blocks.html`.
(3) UK Neil Gehrels Swift Observatory (*Swift*) Science Data Center: `https://www.swift.ac.uk/user_objects/`.
(4) `https://heasarc.gsfc.nasa.gov/docs/software/heasoft/`.

the photometric broad-band filters in optical (v, b, u) and UW (w1, m2, w2) bands. To derive the source instrumental magnitude using `uvotsource`, we adopt a circular source region of $5''$ radius centered at the object position, and a circular nearby region of $20''$ radius to derive the background contamination. Then, we corrected data for the Galactic extinction effect using $E(B-V) = 0.0115 \pm 0.0005$ [14] and we converted the computed magnitudes to energy flux units.

Regarding the radio Very Long Baseline Array (VLBA) data, we analyzed the available visibilities of the Monitoring Of Jets in Active galactic nuclei with VLBA Experiments (MOJAVE) and VLBA-BU-BLAZAR (VLBA-BU-BLAZAR) monitoring programs. We used the Sofware `difmap` and we fitted the brightest components in the visibilities, called knots, using elliptical Gaussian components [15]. Since our long-term study extended to March 2024, we analyzed the public visibilities until April 4th, 2024 for the MOJAVE project, and until March 22nd, 2024 for the VLBA-BU-BLAZAR project, to see if new knots can be detected in the epochs around the γ-ray flares.

3. – Results

Our γ-ray analysis revealed that the source began exhibiting consistent flaring activity at the end of 2021. In this period, the photon index of OP 313 is most of the time harder than the average photon index value (2.14 ± 0.09) weighted in every bin from August 4th, 2008 to March 9th, 2024. We identified the highest γ-ray flares in the 2022–2024 time window.

The number of γ-ray photons seen by *Fermi*-LAT is large enough to study the hysteresis patterns [16] for the identified highest γ-ray flares. The hysteresis pattern gives information about the acceleration and cooling rates of the particles in the blazar's jet. There are two different kinds of hysteresis patterns: clockwise and anti-clockwise patterns. We found both of them for different flares in the 2022–2024 time window.

In 2022 we identified 3 flares. One of them has a comparable flux with the 6 flares we found starting from November 2023, so we decided to include it. For these 7 flares, we studied the double-peak multi-wavelength Spectral Energy Distributions (SEDs). We noticed that the 2 SED peaks of the 2022 selected flare have the same height. On the other hand, the 2 SED peaks of the other 6 flares have different heights. The heights of the 2 peaks of a blazar's SED are linked to the Comptonization [17]. Hence, we can hypothesize that different photon fields coming from inside and outside the jet are involved in the flaring activity of the source from 2022 to 2024.

The results of the publicly available visibilities of the MOJAVE and VLBA-BU-BLAZAR programs from 1995 to 2018 are published in [18-20]. We carried out the analysis of the 15 GHz MOJAVE data from 2019 to 2024. This resulted in a new component which appeared on the 13th of April 2021. The same component was also discovered in the VLBA-BU-BLAZAR. We argue that this component can be responsible for the flaring emission that started in 2022.

4. – Conclusions

OP 313 is an FSRQ characterized by a remarkable flaring activity starting from November 2023. We studied the long-term multi-wavelength emission of this object starting from the beginning of the *Fermi* mission in August 2008. From the multi-wavelength light-curves, we found hints of correlations between the γ-ray emission, the X-ray, the UV, and optical emission. In contrast, the radio emission exhibited a peak in 2008, likely linked to a γ-ray flaring event that occurred prior to the initiation of the Fermi-LAT mission. Subsequently, the radio emission began to increase again around 2019. Focusing on the γ-ray flaring activity, we identified the highest γ-ray flares and we reconstructed the hysteresis patterns to investigate the cooling mechanism and acceleration rates in the jet during the flares. Furthermore, we compared the SED of the flares height of the SED peaks during flares to understand which flare was more Compton dominated than the other. This comparison is useful to identify if there is a photon field coming from outside the jet that is involved in the Inverse Compton emission. Finally, we did a VLBA analysis of the public visibilities of the MOJAVE and VLBA-BU-BLAZAR to see if new components, arising in the jet, can be responsible for the observed flaring emission.

More details and insights on the analysis of OP 313 and its interpretation will be presented in a dedicated publication.

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